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Direct Detection of Dark Matter Degenerate with Colored Particles in Mass

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Abstract

In this Letter we explore the direct detection of the dark matter in the universe, assuming the dark matter particles are degenerate in mass with new colored particles below TeV scale. The scenario with such a mass spectrum is difficult to be confirmed or excluded by the present analysis at the LHC experiments because the QCD jets in the cascade decay of the new particles produced in the proton-proton collision are too soft to be triggered in the event selection. It is shown that both of the spin-independent and spin-dependent couplings of the dark matter with a nucleon are enhanced and the scattering cross section may reach even the current bound of the direct detection experiments. Then such a degenerate scenario may be tested in the direct detection experiments.

1 Introduction

A variety of observational evidences indicate the existence of non-baryonic dark matter (DM). The latest cosmological observations including the WMAP reveal that dark matter accounts for about 83% of the energy density of matter in the universe [1]. The standard model (SM) in particle physics, however, does not explain its existence, and its identification has been a challenge in both particle physics and cosmology. There are several candidates proposed for the dark matter in physics beyond the SM. One of the most attractive candidates is so-called Weakly Interacting Massive Particles (WIMPs), which interact with ordinary matter only through weak and gravitational interactions. In the WIMP DM scenario, WIMPs are supposed to be stable and produced in the thermal history of the universe. Then naturally their relic explains the present abundance of dark matter with the mass around TeV scale.

Nowadays we are reaching to the energy frontier of the TeV scale at the collider experiments. At the Large Hadron Collider (LHC), where protons are colliding at the center of mass energy of 7 TeV, the WIMP dark matter is expected to be produced and observed as large missing energy. In addition, several extensions of the SM also include heavy colored particles which interact with WIMPs directly or via gauge bosons. Once they are produced at the collider, they subsequently decay into WIMPs accompanied by high energy QCD jets. That is why the main strategy for probing such new models is based on events with hard jets and large missing transverse energy. The LHC experiments have already presented results for several models, and put severe constraints on them as no excess above the SM background has been observed. For example, the exclusion limits for the Constrained Minimal Supersymmetric Standard Model (CMSSM) are presented in Refs. [2, 3]. However, the constraints are not directly applied if the colored particles are nearly degenerate with the WIMPs in mass [4]. In this case, the leading jets in most events are too soft to pass the signal selection, and thus it is difficult to confirm or exclude such scenario at the LHC.

In this Letter, we study possibilities for probing this scenario in terms of the direct detection experiments of the dark matter in the universe. We found that both of the spin-independent (SI) and spin-dependent (SD) couplings of the WIMPs with a nucleon are enhanced when the masses of colored particles which mediate the scattering are degenerate with that of WIMPs. This implies that DM direct detection experiments offer a promising way to investigate the degenerate scenario.

The ongoing direct detection experiments have extremely high sensitivities. For example, XENON100 currently gives the most stringent constraint on the SI WIMP DM-nucleon elastic scattering cross sections, $\sigma_{\rm SI} < 7.0\times10^{-45}$ cm^2 for a WIMP mass of 50 GeV [5]. Moreover, there are several proposals to use ton-scale detectors in the future, which are designed to detect WIMPs with sensitivities much below the current limit. Recently a proposal for a future WIMP search experiment, which is planning to achieve a sensitivity of the SI cross section, 10^{-49} cm^2, is announced [6]. With regard to the SD cross section, the IceCube detector would offer excellent sensitivities to it [7]. It has provided upper limits on the SD cross section of WIMPs with a nucleon, $\sigma_{\rm SD} < 10^{-(39-40)}$ cm^2 with

WIMP mass in the range of 100 GeV–1 TeV, and further improvement of the sensitivities by a factor of 2–10 is expected in the same mass range [8, 9].

The scattering cross section of WIMPs with a nucleon is evaluated by using the several effective couplings of WIMPs with quarks and gluon. The precise computation of them is important for the evaluation of the cross section because they may be either destructive [10, 11] or constructive [12], depending on WIMP models. Recently an approach to study nature of the dark matter based on both collider and direct detection experiments in terms of the effective theory is proposed [13, 14]. The authors, however, take just one of the effective couplings into account for the evaluation of the cross sections. In this Letter, we include all of the relevant effective operators into the calculation, and find that the scattering amplitude is enhanced when the masses of colored particles which mediate the scattering are degenerate with that of WIMPs.

In our Letter we study two representative models; the minimal supersymmetric standard model (MSSM) and the minimal universal extra dimension model (MUED). In the MSSM, the lightest superparticle (LSP), which is stabilized by the R parity, is a good candidate for the DM. In this framework, we consider the lightest neutralino, especially Wino-like, DM. Among the components of neutralino, Wino has relatively large coupling to colored particles (*i.e.* squarks) and has a big impact on the cross section. In the MUED model, the Kaluza-Klein (KK) parity protects the lightest KK particle (LKP) from decay, and the LKP is a good candidate for the DM. We consider the scenario where the first excited KK gauge boson is the LKP [15, 16]. There is an earlier literature which studies the complementarity of direct detection and collider searches in the MUED [17]. In their work, however, several effective operators are not considered; thus, the resultant cross sections are smaller than those obtained in Ref. [12], where all of the relevant effective operators are taken into account. We find that the scattering cross sections may reach even the current bound of the direct detection experiments. Although the scattering cross section depends on the details of DM scenarios, our results obtained for the two scenarios describe general aspects of enhancement of cross section in the degenerate scenario.

2 Wino dark matter

Let us study the Wino-like neutralino DM case for a starter. To make discussion simple, we assume the lightest neutralino is close to a pure Wino state. Generalization to other composition of the lightest neutralino is given later.

First of all we give the formulation of the scattering cross section. Wino is a Majorana fermion, and the phenomena of such a fermion scattered by nucleon is described in terms

of the effective Lagrangian given in Refs. [18, 19],

$$
\begin{aligned}
\mathcal{L}_{\rm eff} \;=\; & \sum_q \big(f_q m_q\ \bar{\tilde{W}}^0 \tilde{W}^0 \bar{q} q + d_q \bar{\tilde{W}}^0 \gamma_\mu \gamma_5 \tilde{W}^0 \bar{q} \gamma^\mu \gamma_5 q \\
& + \frac{g_q^{(1)}}{M} \bar{\tilde{W}}^0 i\partial^\mu \gamma^\nu \tilde{W}^0 \mathcal{O}^q_{\mu\nu} + \frac{g_q^{(2)}}{M^2} \bar{\tilde{W}}^0 (i\partial^\mu)(i\partial^\nu) \tilde{W}^0 \mathcal{O}^q_{\mu\nu} \big) \\
& + f_G \bar{\tilde{W}}^0 \tilde{W}^0 G^a_{\mu\nu} G^{a\mu\nu} \,.
\end{aligned} \tag{1}
$$

Here $\tilde{W}^0$ and q denote Wino and light quark with masses M and m_q, respectively, and $G^a_{\mu\nu}$ is the field strength tensor of gluon field. The twist-2 operator, $\mathcal{O}^q_{\mu\nu}$, is defined as $\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2} \bar{q} i \left(D_\mu \gamma_\nu + D_\nu \gamma_\mu - \frac{1}{2} g_{\mu\nu} \not{D} \right) q$ with the covariant derivative D_μ. Then the elastic scattering cross section of DM with nucleon ($N = p, n$) is obtained from the effective Lagrangian as

$$
\sigma_{\tilde{W}^0 N} = \frac{4}{\pi} m_r^2 \left[|f_N|^2 + 3\, |a_N|^2 \right] \,, \tag{2}
$$

where $m_r = M m_N / (M + m_N)$ is the reduced mass with m_N being the nucleon mass. The SI effective coupling, f_N, in Eq. (2) is evaluated by using the nucleon matrix elements of the quark and gluon operators in the effective Lagrangian. The result is

$$
\frac{f_N}{m_N} = \sum_{q=u,d,s} f_q f_{Tq} + \sum_{q=u,d,s,c,b} \frac{3}{4} \left(q(2) + \bar{q}(2) \right) \left(g_q^{(1)} + g_q^{(2)} \right) - \frac{8\pi}{9\alpha_s} f_{TG} f_G \,, \tag{3}
$$

where $\langle N | m_q \bar{q} q | N \rangle / m_N = f_{Tq}$, $f_{TG} = 1 - \sum_{u,d,s} f_{Tq}$ and $\langle N(p) | \mathcal{O}^q_{\mu\nu} | N(p) \rangle = \frac{1}{m_N} (p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu}) (q(2) + \bar{q}(2))$. Here $\alpha_s \equiv g_s^2 / 4\pi$ is the strong coupling constant, and $q(2)$ and $\bar{q}(2)$ indicate the second moments of the parton distribution functions (PDFs). The SD effective coupling, on the other hand, is given as

$$
a_N = \sum_{q=u,d,s} d_q \Delta q_N \,, \tag{4}
$$

where$\langle N | \bar{q} \gamma_\mu \gamma_5 q | N \rangle \equiv 2 s_\mu \Delta q_N$ with s_μ the spin of the nucleon. In this Letter we use the values of these matrix elements given in, *e.g.*, Ref. [19], in which they are evaluated based on works in Refs. [20, 21, 22].

Our remaining task is to calculate the coefficients of the effective operators in Eq. (1). Wino interacts with quarks and gluon via the two types of interactions; the Wino-quark-squark interaction and the weak interaction. The Lagrangian is

$$
\mathcal{L}_{\tilde{W}^0} = \sum_q \sum_{i=1,2} \bar{q} (a_{\tilde{q}_i} + b_{\tilde{q}_i} \gamma_5) \tilde{W}^0 \tilde{q}_i - g_2 (\bar{\tilde{W}}^0 \gamma^\mu \tilde{W}^- W^\dagger_\mu) + \text{h.c.} \,, \tag{5}
$$

where $\tilde{W}^-$ and W_μ represent the charged Wino and the W boson, respectively, and $\tilde{q}_i$ ($i = 1, 2$) denote the squark mass eigenstates. g_2 is the $SU(2)_L$ gauge coupling constant.

The Wino-quark-squark interaction induces tree-level scattering, which gives dominant contribution to the cross section in our present degenerate scenario, as we will see soon. The coefficients $a_{\tilde{q}_i}$ and $b_{\tilde{q}_i}$ depend on the squark mixing angle. The squark mass term is given as

$$\mathcal{L}_{\rm mass} = -\begin{pmatrix}\tilde{q}_L^* & \tilde{q}_R^*\end{pmatrix}\begin{pmatrix} m^2_{\tilde{q}_L} & m^2_{\tilde{q}_{LR}} \\ m^{2*}_{\tilde{q}_{LR}} & m^2_{\tilde{q}_R}\end{pmatrix}\begin{pmatrix}\tilde{q}_L \\ \tilde{q}_R\end{pmatrix}, \tag{6}$$

where $\tilde{q}_L$ and $\tilde{q}_R$ represent the left-handed and right-handed squarks, respectively, and each component is

$$m^2_{\tilde{q}_L,\tilde{q}_R} = \tilde{m}^2_{\tilde{q}_L,\tilde{q}_R} + m_q^2 + D_{\tilde{q}_L,\tilde{q}_R}\,, \tag{7}$$

$$\begin{aligned} m^2_{\tilde{u}_{LR}} &= m_u(A_u^* - \mu\cot\beta)\,, \\ m^2_{\tilde{d}_{LR}} &= m_d(A_d^* - \mu\tan\beta)\,. \end{aligned} \tag{8}$$

Here m_u and m_d indicate up-type and down-type quark masses, and $\tilde{m}^2_{\tilde{q}_L,\tilde{q}_R}$ and A_q are for the soft supersymmetry breaking parameters. μ denotes the supersymmetric mass term of the Higgs superfields. (As we mentioned at the beginning, we consider the pure Wino case. So we take μ much larger than Wino mass in the following numerical calculation.) $\tan\beta$ is the fraction of vacuum expectation values of the up-type and down-type Higgs fields. $D_{\tilde{q}_L,\tilde{q}_R}$ is D-term contribution given as $D_{\tilde{q}_L} = m_Z^2\cos 2\beta(T_q^3 - Q\sin^2\theta_W)$ and $D_{\tilde{q}_R} = m_Z^2\cos 2\beta Q\sin^2\theta_W$. ($m_Z$, θ_W, T_q^3 and Q are the Z boson mass, the weak-mixing angle, $SU(2)_L$ and the electric charge of squark, respectively.) By diagonalizing the mass matrix, we obtain $a_{\tilde{q}_1} = b_{\tilde{q}_1} = -g_2 T^3_{qL}\cos\theta_q/\sqrt{2}$ and $a_{\tilde{q}_2} = b_{\tilde{q}_2} = g_2 T^3_{qL}\sin\theta_q/\sqrt{2}$. Here $\tilde{q}_1$ is the lighter squark and $\sin 2\theta_q \equiv 2m^2_{\tilde{q}_{LR}}/(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})$.

With those expression for $a_{\tilde{q}_i}$ and $b_{\tilde{q}_i}$, the coefficients in the effective coupling in Eq. (3) induced by squark exchange at tree level are derived as follows [18, 19],

$$\begin{aligned} f_q &= \frac{g_2^2 M}{32}\left[\frac{\cos^2\theta_q}{(m^2_{\tilde{q}_1} - M^2)^2} + \frac{\sin^2\theta_q}{(m^2_{\tilde{q}_2} - M^2)^2}\right], \\ d_q &= \frac{g_2^2}{16}\left[\frac{\cos^2\theta_q}{m^2_{\tilde{q}_1} - M^2} + \frac{\sin^2\theta_q}{m^2_{\tilde{q}_2} - M^2}\right], \\ g_q^{(1)} &= \frac{g_2^2 M}{8}\left[\frac{\cos^2\theta_q}{(m^2_{\tilde{q}_1} - M^2)^2} + \frac{\sin^2\theta_q}{(m^2_{\tilde{q}_2} - M^2)^2}\right], \\ g_q^{(2)} &= 0\,. \end{aligned} \tag{9}$$

It is clear in the above expression that they are enhanced when the squark masses are degenerate with the Wino mass. The Wino-squark-quark interaction also induces scattering with gluon at one loop. Although this contribution is $O(\alpha_s)$, it is comparable to the tree-level ones in the SI effective coupling f_N in Eq. (3) since the term proportional to the effective scalar coupling of gluon, f_G, has a factor of $1/\alpha_s$. According to Ref. [19], the gluon contribution is evaluated as

$$f_G = -\frac{\alpha_s g_2^2 M}{384\pi}\left[\frac{\cos^2\theta_q}{m^2_{\tilde{q}_1}(m^2_{\tilde{q}_1} - M^2)} + \frac{\sin^2\theta_q}{m^2_{\tilde{q}_2}(m^2_{\tilde{q}_2} - M^2)}\right]. \tag{10}$$

This result is for the case where only first generation squarks are degenerate with dark matter in mass. We will focus on such a scenario in our numerical calculation, which will be addressed soon. From its explicit expression, it is easily seen that the gluon contribution is also enhanced in the degenerate mass spectrum.

In addition to the squark exchanging process, Wino interacts with quarks and gluons through the weak interaction at loop level. These contributions might be sizable especially in the case where Wino is much heavier than the weak scale since they are not suppressed even in such a spectrum [23]. All of these contributions are evaluated in Ref. [10, 19], and we include them into our numerical calculation.

The phenomena at the LHC in the supersymmetric model is followed by pair production of colored superparticles: $pp \to \tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{g}$ where $\tilde{g}$ is gluino and $\tilde{q}$ is squarks (mainly the first generation squarks). Then subsequent cascading decay of $\tilde{q}$ and $\tilde{g}$ to the LSP yields many QCD jets and missing energy since the LSPs escape from the detectors without tracks. At the present stage of the data analysis, the masses of $\tilde{q}$ and $\tilde{g}$ are constrained nearly up to 1 TeV due to the null signal event [2, 3]. In our Letter, we discuss the case where the Wino LSP is so degenerate with squarks in mass that the missing transverse energy signature would not be observed at the LHC experiments due to soft jets. Since triggers for the leading jets in their analysis are typically set to be above 100 GeV (*e.g.*, the leading jets are required to have the transverse momentum larger than 130 GeV in ATLAS Collaboration [2], while each of the two hardest jets in events must have the transverse energy larger than 100 GeV in CMS Collaboration [3]), the degeneracy of 100 GeV in their masses is enough to conceal the missing energy signals at the present stage of the data analysis at the LHC experiments.[1] Even when the mass difference is 200–300 GeV, it is hard to probe the signature by using the current approach.[2]

For simplicity, we assume the first generation squarks to be degenerate with Wino and the other squarks to be heavy enough to evade the current bound. Gluino is assumed to be either degenerate with Wino or much heavier than the present limit. The degeneracy is parametrized as

$$\Delta m \equiv \tilde{m}_{\tilde{q}_L,\tilde{q}_R} - M \, . \tag{11}$$

Considering the above discussion, we carry out the calculation with the parameter Δm up to 200 GeV.

In Fig. 1, we plot the SI scattering cross section of the Wino DM with a proton as a function of the DM mass. Each line corresponds to the case where $\Delta m = 50$, 100, 150 and 200 GeV from top to bottom. In the figure, the limit by the XENON100 experiment [5] is depicted in a bold line. Here we take the other parameters as $A_{u,d} = 0$, $\mu = M + 1$ TeV, $\tan\beta = 10$ and $m_h = 120$ GeV in order to include the SM Higgs boson contribution to the SI cross section. We have checked that the cross section has little dependence on those parameters. The result given in the figure shows that the SI cross section is considerably enhanced when squarks are degenerate with Wino in mass and it is quite sensitive to

[1] Here we note there are several works which investigate collider signature in the degenerate mass spectrum scenarios by using initial state radiation in the MSSM [24, 25] and M_{T2} in the MUED [26].

[2] We thank S. Asai for his instruction in private communications.

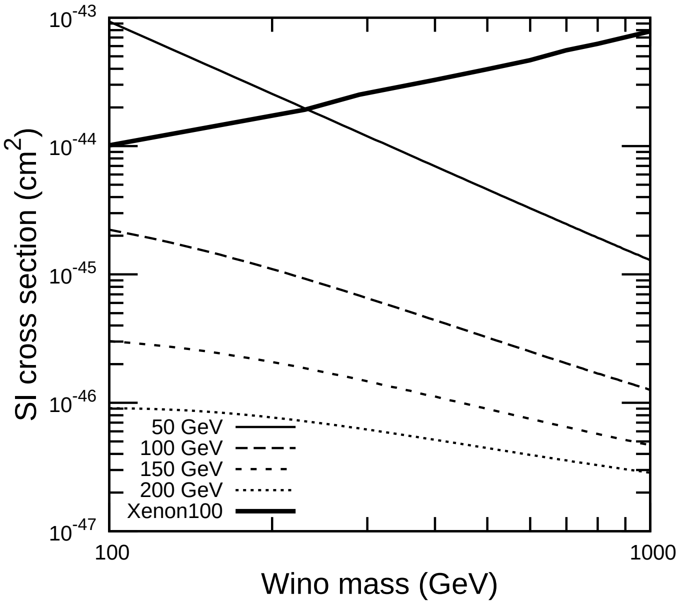

Figure 1: SI scattering cross section of Wino DM with a proton as a function of Wino-like neutralino mass. Each line corresponds to $\Delta m = 50$, 100, 150 and 200 GeV from top to bottom, and upper bound from XENON100 [5] is shown in bold line.

the degeneracy. In the calculation for Fig. 1, we found that the 'twist-2' contribution with coefficient $g_q^{(1)}$ in Eq. (3) is the main contribution as expected from Eq. (9). When $\Delta m = 50$ GeV, the Wino mass of less than 200 GeV is excluded by the XENON100 result. Even in the case of $\Delta m = 200$ GeV the SI cross section is 10^{-46}–10^{-47} cm^2 for $M = 100$ GeV–1 TeV. Such a value of the cross section would be tested by future experiments.

We can also consider the case where other squarks, *e.g.,* the third generation squarks, are degenerate with the lightest neutralino in mass instead of the first generation squarks. In such cases, the scattering cross section tends to be rather small because the tree-level contribution is suppressed. However, in some parameter region, the SI cross section could be large enough to be accessible in the future direct detection experiment.

Next we show the SD scattering cross section of Wino DM with a proton as a function of Wino mass in Fig. 2. In the plot the parameters are taken to be the same values as those for the SI cross section evaluated above. We observe the similar enhancement due to the mass degeneracy of DM with squarks in the SD scattering cross section, as is expected. When $\Delta m \lesssim 100$ GeV, the SD cross section is comparable to the sensitivity of IceCube experiment, $\sigma_{\rm SD} \lesssim 10^{-(40-41)}$ cm^2 [8].

So far we have discussed the pure Wino DM scenario. To end this section, we give some comments on the extension to more general neutralino DM. When μ is not extremely large compared to the weak scale, the lightest neutralino is no longer a pure Wino state, rather the mixed state of Bino, Wino and Higgsinos. For example, the Wino-like neutralino

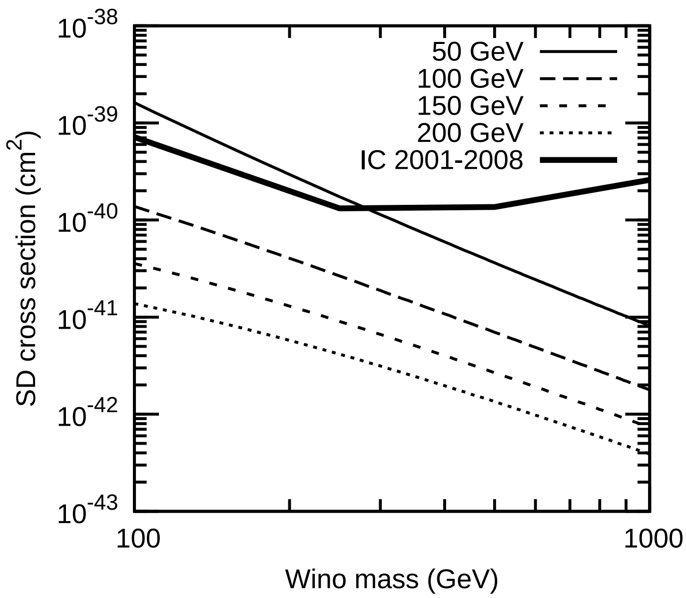

Figure 2: SD scattering cross section of Wino DM with a proton as a function of Wino-like neutralino mass. Parameters in this plot and line contents are the same as Fig. 1. Preliminary IceCube bound [8] is also shown in bold line. This bound is given by assuming WW final state, which is suitable for our present Wino DM.

interacts with the Higgs bosons (SM-like and heavy Higgs bosons) and the Z boson via mixing with Higgsinos, which gives rise to the Higgs boson exchange in the SI scattering and the Z boson exchange in the SD scattering, respectively. We computed these types of contributions and found that they might have sizable effects. When $\mu \lesssim M+400$ GeV, the contribution from the SM-like Higgs boson exchange has the opposite sign of the twist-2 contribution and its absolute value may be comparable to the twist-2 contribution. On the other hand, the heavy Higgs boson contribution depends on the sign of μ, the heavy Higgs boson mass and $\tan\beta$. If μ is positive, this contribution has the same sign as the twist-2 contribution and vice versa. As to its absolute value, it is suppressed by the heavy Higgs boson mass, while it is enhanced by $\tan\beta$. When $\tan\beta$ is large (*e.g.*, ~ 30), it gives a contribution to the effective coupling, almost comparable to the SM-like Higgs one, despite the large mass of the heavy Higgs boson around 1 TeV. Therefore this type of Higgs contribution could be either constructive or destructive in the SI effective coupling, depending on the parameters in the Higgs sector in the MSSM. The Z boson exchange process also might yield a sizable effect to the SD cross section, however, the squark exchange process tends to dominate the effective coupling in the degenerate scenario.

As regards Bino-like and Higgsino-like neutralino DM, we have also evaluated their impact on the scattering cross sections with nucleon. In the case of Bino-like DM, we found that the cross section is in general smaller than that of Wino DM. For Higgsino-like DM, the cross section is also suppressed due to its considerably small couplings to the

first and second generation squarks unless the gaugino-Higgsino mixing is sizable. The details will be given elsewhere [27].

3 Kaluza-Klein dark matter

In this section, we consider the case of LKP DM in the framework of MUED model. In the MUED model, we consider the first excited state of the $U(1)_Y$ B boson, $B_\mu^{(1)}$, is the LKP and becomes the dark matter. The effective Lagrangian of such vector dark matter with quarks and gluon is formulated in Ref. [12]:

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= \sum_q \bigl(f_q m_q B^\mu B_\mu \bar{q}q + \frac{d_q}{M}\epsilon_{\mu\nu\rho\sigma} B^\mu i\partial^\nu B^\rho \bar{q}\gamma^\sigma\gamma^5 q + \frac{g_q}{M^2} B^\rho i\partial^\mu i\partial^\nu B_\rho \mathcal{O}^q_{\mu\nu}\bigr) \\ &\quad + f_G B^\rho B_\rho G^{a\mu\nu} G^a_{\mu\nu}\,, \end{aligned} \tag{12}$$

where $\epsilon^{\mu\nu\rho\sigma}$ is the totally antisymmetric tensor defined as $\epsilon^{0123} = +1$. Here we omit the superscript of $B_\mu^{(1)}$ for simple expression. In this case the elastic scattering cross section of the DM with nucleon is given as

$$\sigma_{B^{(1)}N} = \frac{m_r^2}{\pi M^2}\left[|f_N|^2 + 2\,|a_N|^2\right]\,. \tag{13}$$

In this case, the SI effective coupling is given by Eq. (3) in which $(g_q^{(1)} + g_q^{(2)})$ is replaced by g_q, and the SD effective coupling is expressed the same as given by Eq. (4). All of the coefficients of the effective operators in Eq. (12) are computed in Ref. [12]. The tree-level contributions are

$$\begin{aligned} f_q &= -\frac{g_1^2}{4m_h^2} - \frac{g_1^2}{4}\left[Y_{\text{qL}}^2 \frac{m_{Q^{(1)}}^2}{(m_{Q^{(1)}}^2 - M^2)^2} + Y_{\text{qR}}^2 \frac{m_{q^{(1)}}^2}{(m_{q^{(1)}}^2 - M^2)^2}\right] \\ &\quad + \frac{g_1^2 Y_{\text{qL}} Y_{\text{qR}}}{m_{Q^{(1)}} + m_{q^{(1)}}}\left[\frac{m_{Q^{(1)}}}{m_{Q^{(1)}}^2 - M^2} + \frac{m_{q^{(1)}}}{m_{q^{(1)}}^2 - M^2}\right], \end{aligned} \tag{14}$$

$$d_q = \frac{i g_1^2 M}{2}\left[\frac{Y_{\text{qL}}^2}{m_{Q^{(1)}}^2 - M^2} + \frac{Y_{\text{qR}}^2}{m_{q^{(1)}}^2 - M^2}\right], \tag{15}$$

$$g_q = -g_1^2 M^2 \left[\frac{Y_{\text{qL}}^2}{(m_{Q^{(1)}}^2 - M^2)^2} + \frac{Y_{\text{qR}}^2}{(m_{q^{(1)}}^2 - M^2)^2}\right]. \tag{16}$$

Here $q^{(1)}$ and $Q^{(1)}$ describe the mass eigenstates of the first KK quarks which are $SU(2)_L$ singlet and doublet with masses $m_{q^{(1)}}^2$ and $m_{Q^{(1)}}^2$, respectively. Y_{qL} and Y_{qR} are the hypercharges of left-handed and right-handed quarks, and g_1 is the $U(1)_Y$ gauge coupling constant. The first term in Eq. (14) corresponds to the SM Higgs boson exchange contribution, while the other terms come from the KK quark exchange processes. The KK quark-exchange processes turn out to be enhanced when their masses are degenerate with the DM mass, similarly to the previous Wino case. For the gluon contribution, we use

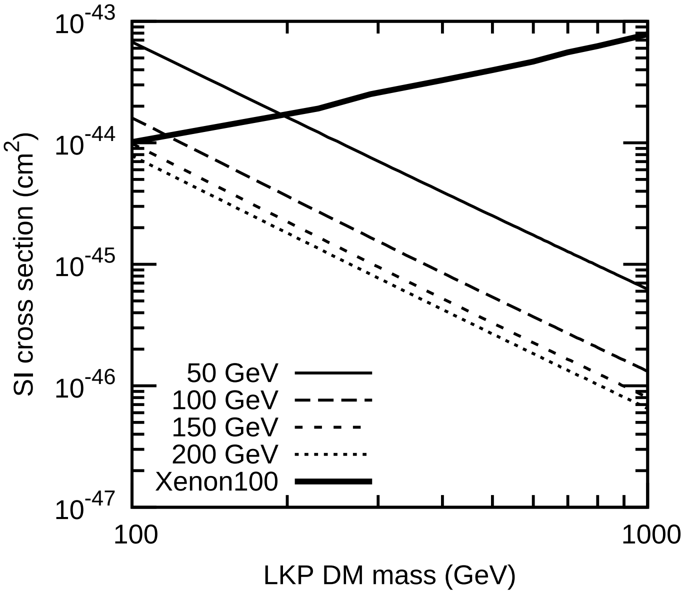

Figure 3: SI scattering cross section of LKP DM with a proton as a function of DM mass. From top to bottom $\Delta m = 50$, 100, 150 and 200 GeV, and XENON100 limit is also shown in bold line [5].

the results in Ref. [12]. To make our discussion simple, we take mass parameters of the first KK quarks $m_{q1,Q1}$ as

$$m_{q1,Q1} = M + \Delta m \tag{17}$$

to give $m^2_{q^{(1)},Q^{(1)}} = m^2_{q1,Q1} + m^2_q$, and consider the parameter region $\Delta m \lesssim 200$ GeV. Such mass degeneracy is generally obtained in the MUED model since the mass of each KK mode at tree-level is just determined by the radius of the extra dimension.

Now we are ready to evaluate the SI cross section of LKP DM with a proton. Fig. 3 illustrates the results for the cross section as a function of LKP DM mass. In the figure, we take $\Delta m = 50$, 100, 150 and 200 GeV from top to bottom. The SM Higgs boson mass is set to be 120 GeV. It is found that the SI cross section is enhanced as the mass difference Δm becomes small, while the dependence of Δm on the SI cross section is weaker compared to the Wino-like neutralino DM case. This is due to the SM Higgs boson exchange contribution, which does not depend on Δm. It becomes sizable in the effective coupling when the other contributions are suppressed with large Δm.

We show the result for the SD cross section in Fig. 4. The parameters are taken the same as in Fig. 3. As in the previous pure Wino scenario, the small mass difference leads to the large SD scattering cross section. This fact indicates that the experiments which observe the SD cross section would provide property of the dark matter.

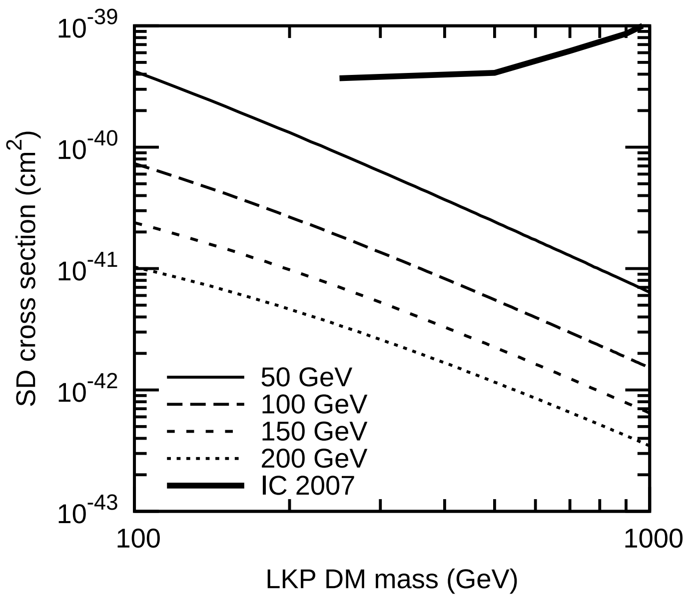

Figure 4: SD scattering cross section of LKP DM with a proton as a function of DM mass. Parameters are taken the same as in Fig. 3. Bold line shows IceCube bound for LKP DM given in Ref. [9].

4 Conclusion

In this Letter we have investigated direct detection of WIMP dark matter degenerate with new colored particles in mass. We considered the scenario where WIMP dark matter interacts with new colored particles and quarks. As typical examples, we studied the Wino DM in the MSSM and the LKP DM in the MUED. Then we found that the scattering cross section of the DM with nucleon reaches the current bound when mass difference of the colored particle and DM is less than about 100 GeV with the DM mass below 1 TeV. This result shows that the current and future direct detection experiments might shed light on the nature of dark matter and new colored particles when their masses are degenerate.

Acknowledgments

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